Galaxy Disruption in a Halo of Dark Matter

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Abstract
The relics of disrupted satellite galaxies around the Milky Way and Andromeda have been found, but direct evidence of a satellite galaxy in the early stages of being disrupted has remained elusive. We have discovered a dwarf satellite galaxy in the process of being torn apart by gravitational tidal forces as it merges with a larger galaxy's dark matter halo. Our results illustrate the morphological transformation of dwarf galaxies by tidal interaction and the continued build-up of galaxy halos.

A long standing problem with the theory of a hierarchical universe consisting of cold dark matter halos (1,2) is that it over-predicts the number of small dwarf satellite galaxies (3). Some satellites have been accreted by their host galaxy, and the stars from these disrupted satellites have been found in the Milky Way (4,5,6) and Andromeda galaxies (7). However, the accretion time for most satellites is sufficiently long that we would expect many of them to survive to the present day (8). As a satellite orbits within a halo it will be subject to tidal interaction effects which cause its outer stars to be stripped away forming extended tails (9, 10). These tails trace out the orbit of the dwarf, becoming a relic stream within the larger galaxy's halo. Dwarfs containing a disk will have their disk disrupted. A tidal encounter may also create a bar which drives gas to the galaxy center, inducing a burst of star formation. This raises the central surface brightness and makes the galaxy more compact.

As part of its early release observations, the new Advanced Camera for Surveys (ACS) installed on the Hubble Space Telescope obtained a deep multi-color image of UGC 10214 (the Tadpole galaxy) in April 2002 (11,12). The ACS image also contained an edge-on spiral galaxy $\sim 1.5'$ northeast of UGC 10214. The spiral is barely visible on the Digital Sky Survey and is uncatalogued in the NASA Extragalactic Database. We have determined a position of α = 16:06:11, δ=+55:26:57 (J2000). To the north of the spiral, at a projected separation of 6.4" and close to its minor axis, lies a small galaxy with extended tails of starlight (Fig. 1). There is also an indication that the spiral galaxy disk is warped (Fig. 2), a feature that may be caused by an interaction with a satellite galaxy. Although suggestive, confirmation of a physical association requires that the dwarf galaxy and the large spiral have a similar redshift.

During an observing run in March 2003 on the Keck telescope, we obtained a short exposure image in which the spiral, the dwarf and its tails were all visible. A spectrograph slit was aligned across the nuclei of both galaxies. Spectra with a 1 hour exposure time were taken and reduced using standard procedures (13). We obtained a spectrum of the dwarf with a signal-to-noise ratio of $\sim$5 and measured a heliocentric recession velocity of 43,445 $\pm$ 225 km/s (or redshift z = 0.145). For the spiral we measured 43,433 $\pm$ 90 km/s. The

Assuming a ΛCDM Universe (with $\Omega_\Lambda = 0.7$ and Hubble constant $H_o = 75$ km/s/Mpc), this redshift implies that the two galaxies have a projected separation of 16 kpc (1" $\sim$ 2.5 kpc).

The ACS images consist of deep exposures in the filters F475W (g'), F606W (broad V) and F814W (I). They have been aligned to within 1/3 of a pixel (each ACS pixel is $\sim$0.05"). Using zero points on the AB system (11), and a K-correction for redshift, we derive rest-frame magnitudes and surface brightnesses (after correcting for a $(1+z)^4$ dimming effect). No correction for Galactic extinction is applied as it is small ($A_V < 0.03$). With an aperture specially-designed to match the shape of the spiral galaxy, we estimate its total Johnson V band magnitude to be 18.0. This corresponds to an absolute magnitude M_V of –21.0 (correction to a face-on magnitude could make the galaxy more luminous by about one magnitude). Assuming an intrinsic disk flattening of 0.1, we estimate that the spiral is of type Sb and is inclined at 70 ± 5^o to the line-of-sight.

The dwarf galaxy consists of an elongated main body, which has a diameter of $\sim$1.5" (3.8 kpc), from which the tails extend. The northern tail is better defined. After about 7.8" (20 kpc) it bends and extends an additional 7.5" (19 kpc). This tail has an average V band surface brightness of 26 mag/sq. arcsec. The southern tail is visible for 6.4" (16 kpc) where it becomes confused with the spiral galaxy starlight. There is a hint that it appears on the other side of the spiral (Fig. 2) with a surface brightness of 26.5 mag/sq. arcsec. For the main body of the dwarf, we estimate an absolute magnitude M_V = –16.0. The total luminosity of the tails is more difficult to quantify, but we estimate that there is at least as much starlight in the tails as in the main body of the dwarf. Thus the original galaxy may have been twice as luminous as it is now, i.e. $M_V \sim$ –16.8. From the local galaxy scaling relation, this magnitude would correspond to a mean metallicity of [Fe/H] $\sim$ –0.9 (14).

In the dwarf's central regions its color remains fairly constant with radius at B–V = 0.34 and V–I = 0.5. These relatively blue colors suggest the presence of young stars. We compared the dwarf colors to a stellar population model (15) to determine its age. The model indicates a mean metallicity [Fe/H] = –0.7 with a range of 0 to –1, and a luminosity-weighted age of 2 ± 1 Gyr. Thus, the model suggests that the dwarf had a burst of star formation a few billion years ago. The tails are 0.1-0.2 magnitudes bluer than the main body of the dwarf.

We have fitted the dwarf galaxy isophotes with the IRAF program ellipse. The resulting surface brightness, ellipticity and position angle profiles of the model fit (Fig. 3) show that the dwarf has a position angle twist from near 0^o at the center to about -20^o in its outer parts. The ellipticity also varies over this radial range from nearly circular to elliptical at radii where the tails begin to dominate the starlight. A Sersic profile (16) has been fit to the galaxy surface brightness within the main body (further out, the galaxy has excess light compared to a Sersic profile). The fit for each filter gives similar results. For the F606W filter we measure a Sersic n value of 1.28 ± 0.08. This value would suggest a central black hole mass of $\sim 5 \times 10^6$ solar masses from the local galaxy correlation (17). We measure an effective radius (Re) of 0.37 ± 0.03" (0.93 +/- 0.08 kpc) and the surface brightness in the V band at this radius (μ_e) of 22.7 ± 0.1 mag/sq. arcsec. The central surface brightness (μ_o) is estimated to be 20.8 ± 0.2 mag/sq. arcsec. These structural and photometric properties for the dwarf main body resemble those of dwarf elliptical (dE) galaxies (18, 19).

Fig. 4 compares the photometric properties of the dwarf main body with nearby dwarf galaxies. It lies in a region of the diagram occupied by dIrr and dE galaxies. As the starburst

NGC 205, which has similar photometric properties to our ACS dwarf galaxy. This satellite of M31 is classified as a dE/dSph with a bright nucleus. It also reveals evidence for a young starburst and twisted outer isophotes (21, 22). These features suggest that NGC 205 has experienced gas inflow which induced a nuclear starburst and has undergone tidal shredding of its outer regions. The location of the Sagittarius dSph, which is currently undergoing its final disruption and accretion by our Galaxy (4), is also shown.

The relatively high surface brightness of the tails suggests that the progenitor galaxy contained a disk (10). This is further supported by our estimates of a young starburst, which requires gas and hence a disk. Thus the progenitor may have been a dwarf irregular (dIrr) galaxy. Simulations of galaxy interactions have shown that dIrr galaxies can be tidally disrupted in the halos of large galaxies and transformed to resemble dE and dSph galaxies (10). This process also explains why dE and dSph galaxies are preferentially found in the extended halo of giant galaxies, while dIrr galaxies are generally located in isolated regions (23).

Whether or not the dwarf fully merges with the host spiral depends on the dynamical friction time-scale. This can be estimated, based on the observed luminosity of the dwarf and spiral, and assuming a mass-to-light ratio of 10 for both galaxies. The main uncertainty in estimating this time-scale is the true separation between the galaxies at the start of the dwarf's orbit. If we assume a separation of 50 kpc (corresponding to the extent of the northern tail) then the time-scale to fully merge is twice the current age of the Universe. As the dwarf loses mass by tidal disruption the dynamical friction time-scale becomes even longer, slowing the orbital decay further.

Simulations of dwarf satellites suggest they have highly elongated orbits (24) and typically produce tails of low surface brightness, e.g. 28-30 mag/sq. arcsec (9,10). So the satellites spend much of their orbit at a large distance from the host galaxy and generally produce tails that are extremely difficult to detect. Here we are witnessing a dwarf that is currently close to its host galaxy and has relatively high surface brightness tails from its disk stars.

Until now, clear observational evidence for a dwarf satellite actually in the process of being tidally disrupted within the halo of a larger galaxy was lacking. Our results indicate that spiral galaxy halos are still being built hierarchically as recently as 2 Gyrs ago (the look-back time for $z = 0.145$), providing further evidence for the diversity of the stars in galaxy halos (25). Our results also provide observational support for the suggestion that dIrr galaxies can be morphologically transformed into dE and dSph galaxies (20).

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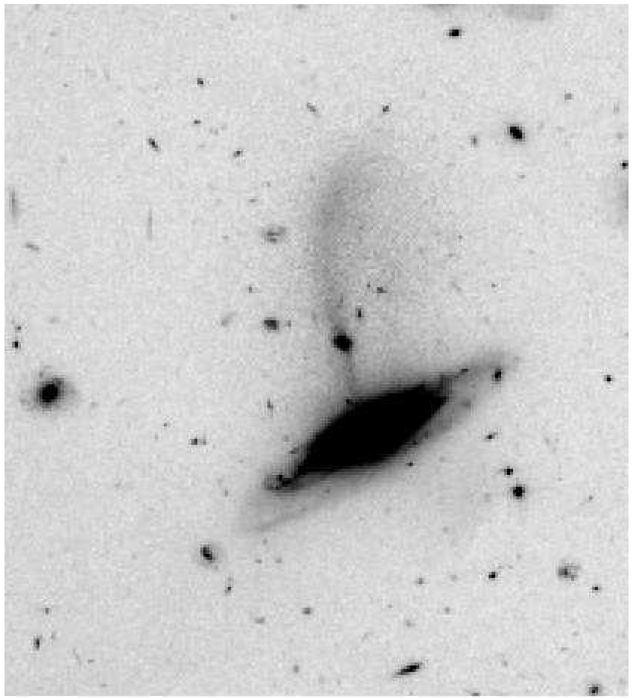

Figure 1: Original image from the Advanced Camera for Surveys (ACS) on board the Hubble Space Telescope. The image shows an edge-on spiral and a dwarf galaxy with extended tails of starlight. The image is 70" × 72" in size.

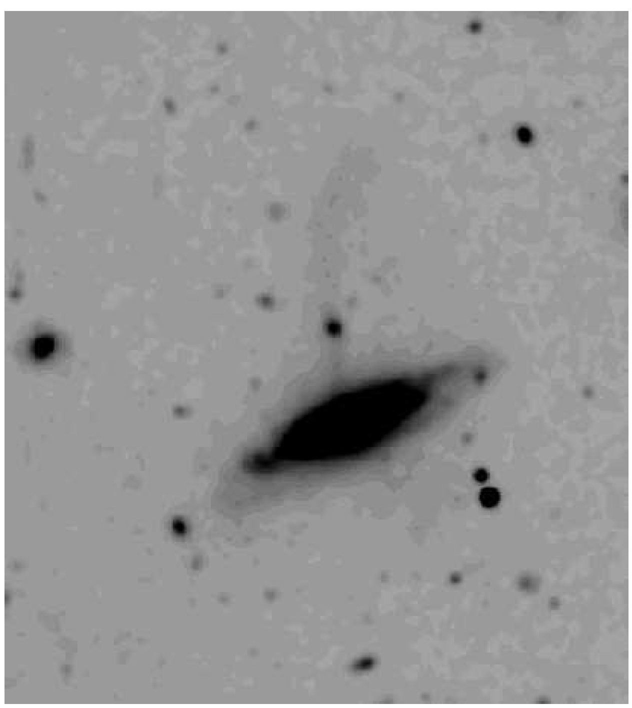

Figure 2: A smoothed ACS image which reveals low surface brightness features better than Fig. 1. There is a hint of light on the lower right side of the spiral which may also be associated with the dwarf galaxy. The spiral shows a possible warped disk at low surface

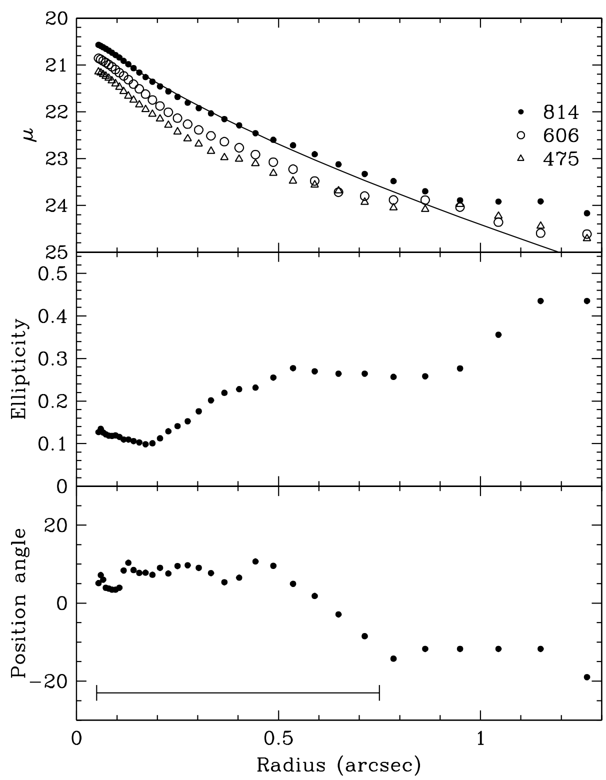

Figure 3: Surface brightness, ellipticity and position angle profiles for the dwarf galaxy from a fit to the galaxy isophotes. The surface brightness profiles (μ) are shown for the Hubble Space Telescope filters F475W (g$'$), F606W (broad V) and F814W (I), with a Sersic fit to the F814W profile. The horizontal line indicates the main body of the dwarf to a radius of $0.75''$ (1.9 kpc).

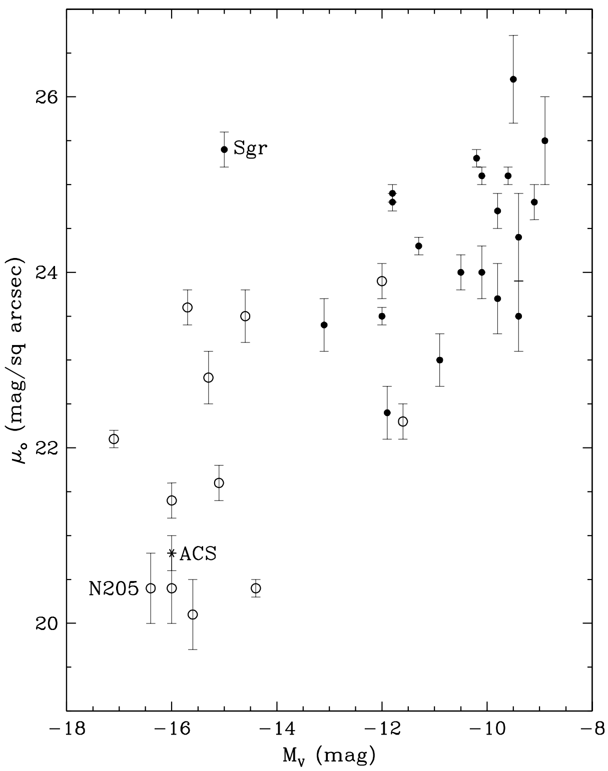

Figure 4: Central V band surface brightness plotted against galaxy luminosity for nearby dwarf galaxies (20). The open symbols represent dwarf irregular (dIrr) and elliptical (dE) galaxies, the filled symbols show dwarf spheroidals (dSph). The location of the dwarf seen in the ACS Hubble Space Telescope image, NGC 205 and the Sagittarius dwarf galaxy are labelled. As the starburst in the ACS-imaged dwarf fades and it continues to lose mass via tidal shredding it will move towards the upper right in this diagram.